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WEAPONS SYSTEMS RESEARCH LABORATORY

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TECHNICAL REPORT

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FLIGHT TESTS OF VARIOUS MK82 BOMB CONFIGURATIONS

R.E. DUDLEY and R.L. POPE

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R.E. Dudley and R.L. Pope

S U M M A R Y

A series of fifteen 1/2 scale models of the Mk82 bomb has been fired from the Weapons Systems Research Laboratory gas gun with a nominal muzzle velocity of 120 m/s. The object of the trials was to compare the performance of various configurations, including streamlined models, models with lugs and fuses and some models with a modified tail cone. Three of the vehicles tested were the standard streamlined wind tunnel shape and the results from these are used as a benchmark in assessing the performance of the other configurations. Some of the trials were only partially successful and no data at all was obtained from two of the trials. However, all available results are presented and an assessment made of the relative performance of each configuration. Some comparisons are also made with wind tunnel measurements. The most striking aspect of the results is the 100% increase in drag resulting from the addition of lugs and fuses.

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1. INTRODUCTION

Wind tunnel measurements of the aerodynamic forces and moments which act on a Mk82 bomb have been carried out in most instances on a somewhat idealised representation of the actual weapon. Until recently, no data has been available from wind tunnel tests of models incorporating the nose and tail fuses and the twin T-lugs as they are used on that version of the Mk82 bomb currently in service with the RAAF. In addition much of the data which is available has been obtained using wind tunnel models with an enlarged base. In general it is necessary to enlarge the base of a small scale wind tunnel model to allow room for the sting on which the model is mounted. Thus the primary aim of the trials described in this report is to compare the flight performance of the streamlined, idealised version of the Mk82 bomb and the performance of the version with twin lugs and nose and tail fuses. A sketch of the basic streamlined model appears in figure 1. Attachment points for the lugs and the tail fuse are indicated on the sketch. The lugs and fuses themselves are shown in figure 2. Figure 3 is a photograph of the model with nose and tail fuses and lugs attached. A second aim of the trials has been to assess the effectiveness of a modification to the tail cone which was intended to reduce the carriage drag and improve the transonic stability of the bomb. The modified tail cone is shown in figure 4. The third objective of the trials has been a detailed assessment of the accuracy and reliability of the double flashing light trials technique for measuring the flight behaviour of missiles and of deriving their aerodynamics.

A number of trials was conducted on the Weapons Systems Research Laboratory (WSRL) gas gun range to satisfy these aims, using models containing two flashing lights one in the nose and the other in the tail. A detailed description of the trials and the bomb configurations which were tested can be found in Section 2. The data obtained was analysed using a parameter estimation algorithm to derive values for the basic aerodynamic derivatives. A full description of the trials technique and the data analysis method is given in references 1, 2 and 3. Section 3 summarises the results of the trials and analysis of the data and compares the performance of the different configurations. There are also some comparisons with wind tunnel results in this section. We summarise, in Section 4, the important results which were obtained from the trials and, in Section 5, we give our main conclusions about the trials.

2. TRIALS

Four different configurations of the Mk82 bomb were used in the trials. The first configuration was a half scale model of the basic streamlined bomb shape. A sketch of the model appears in figure 1. The forebody and afterbody of the model were made of wood. Flashing lights with perspex covers were mounted at the nose and just forward of the fins in the tail cone. The cylindrical centre section was constructed of aluminium alloy. The last five vehicles were fitted with a small continuous light in this section to provide additional roll rate data. The second configuration had the lugs and fuses sketched in figure 2 attached. The nose fuse arrangement replaced the perspex nose cap and the two lugs and tail fuse were attached in the positions indicated in figure 1. A photograph of a model with nose fuse, tail fuse and lugs attached, is shown in figure 3. The third and fourth configurations were similar to the first and second respectively, but the tail cone was modified as shown in figure 4. The vehicles were numbered serially from DFL6 onwards and the configuration for each vehicle is indicated in Table 1. Vehicles DFL7 and DFL8 have not been included because no data was obtained from either. The nose of the former fell off at launch while the sabot for the latter disintegrated in the gun barrel. Originally it was intended that two vehicles of each configuration would be flown, totalling eight altogether. However, the quality of the data obtained from DFL12, 13 and 14 was not up to expectations and therefore a further three rounds DFL16, 17 and 18 were flown as replacements. Rounds DFL19 and DFL20 were flown as development rounds to provide data for developing and testing methods of analysis, but are included here because they also provided data relevant to this study. The models with unmodified tails, DFL6, 9, 10, 15, 19 and 20 carried magnetometers and telemetry transmitters to provide data on roll behaviour. However, due to problems with frequency drift in the transmitter no roll data was obtained from DFL9 and DFL10 and only a little from DFL19.

TABLE 1. VEHICLE CONFIGURATION

Serial No.	Streamlined	Lugs and Fuses	Modified Tail	Magnetometer
6	yes	no	no	yes
9	no	yes	no	yes
10	yes	no	no	yes
11	yes	no	yes	no
12	no	yes	yes	no
13	yes	no	yes	no
14	no	yes	yes	no
15	no	yes	no	yes
16 (13)	yes	no	yes	no
17 (12)	no	yes	yes	no
18 (14)	no	yes	yes	no
19	no	yes	no	yes
20	yes	no	no	yes

NOTE: DFL7 and DFL8 were both streamlined bombs with unmodified tails but are not included because neither provided any data.

The mass and inertias of each bomb model are given in Table 2, and launch conditions and wind speed and direction, are listed in Table 3. The launch velocity of each model was restricted by the range safety requirement that the impact range of the vehicle should not exceed 1000 m. In general, trials were not attempted when wind speeds were such as to present serious difficulties to the data analysis procedure.

A detailed description of the trials technique is given in reference 1. Briefly, the flashing lights on the bomb are recorded by up to five ballistic cameras. The position of the lights at each flash is determined by triangulation. Trajectory of the centre of gravity is determined by averaging the positions of the two lights and the angular behaviour of the bomb is determined by differencing the positions of the two lights. The data obtained is processed by a parameter estimation algorithm to obtain the basic aerodynamic coefficients.

3. RESULTS

The results of the double flashing light trials are discussed from two separate points of view. In the first half of this section, we look at each of the trials individually. The accuracy and consistency of the data from the trials is a good guide to the reliability of the flashing light technique. The second half of the section is devoted to overall consideration of the results, particularly with regard to the values derived for the aerodynamic derivatives.

TABLE 2. VEHICLE PHYSICAL DATA

Serial No.	Mass (kg)	Pitch inertia (kg m^2)	Roll inertia (kg m^2)
6	11.57	0.689	0.0260
9	13.61	0.710	0.0264
10	12.93	0.710	0.0264
11	13.61	0.821	0.0263
12	13.00	0.811	0.0259
13	12.78	0.821	0.0263
14	12.86	0.811	0.0259
15	13.20	0.710	0.0264
16	12.70	0.821	0.0263
17	13.10	0.811	0.0259
18	13.10	0.811	0.0259
19	14.80	0.854	0.0264
20	13.92	0.810	0.0260

body diameter = 0.1365 m
cross-sectional area = 0.01463 m^2
centre of gravity = 3.59 calibres, aft of the nose, midway between the lug positions

TABLE 3. TRIAL CONDITIONS

Serial No.	Launch conditions		Wind	
	Nominal velocity (m/s)	QE (degrees)	Velocity (m/s)	Direction (°T)
6	114	17	4	120
9	115	21	2	60
10	117	22	3	120
11	113	21	4	120
12	125	22	6	190
13	102	22	4	170
14	123	21	5	170
15	116	22	2	20
16	112	21	5	195
17	120	22	6	175
18	117	21	8	155
19	117	20	3	134
20	119	21	3	190

NOTE: The range centre line is at 313°T

3.1 Experimental data

In this section we discuss the quality of the data from each trial together with various other factors affecting the results obtained from each double flashing light model. The conclusions regarding the quality of the data from each trial will help in assessing the reliability of the results from each trial and in assessing the overall accuracy of the trials method. In

Table 4 we present average root mean square noise levels for each component of velocity of the centre of gravity of the model and the angles of azimuth and elevation of its longitudinal axis. These results indicate the overall quality of the data from each trial. During the data analysis, the parameter estimation algorithm fits a theoretical trajectory model to the measured flight data by minimising the sum of the squares of the weighted residuals of measured values of the five data components relative to theoretically generated values. The residual for each data component is weighted in inverse proportion to the noise level quoted in Table 4, so that the importance of each data component in determining parameter values is in inverse proportion to its average RMS noise level. Table 5 lists the estimated apparent average distance between the nose and tail lights for each vehicle. The standard deviation of each estimate is also shown. The weighted mean of all the estimates is 0.9281 m, each estimate being weighted according to the inverse of its rms error. The standard deviation of the distance estimates is a very accurate measure of the quality of the data from each trial.

TABLE 4. RMS NOISE LEVELS IN DATA

Round	$\dot{x}$	$\dot{y}$	$\dot{z}$	ψ	θ
		(m/s)		(radians)	
6	0.79	1.56	1.05	0.217	0.122
9	0.76	0.61	0.40	0.099	0.035
10	0.48	0.47	0.12	0.054	0.015
11	1.12	0.63	0.30	0.119	0.037
12	0.63	0.60	0.21	0.073	0.024
13	0.18	0.12	0.13	0.012	0.011
14	0.74	0.86	0.38	0.041	0.038
15	0.26	0.29	0.30	0.020	0.016
16	0.64	0.61	0.17	0.043	0.012
17	0.39	0.26	0.37	0.043	0.037
18	0.57	0.67	0.62	0.054	0.038
19	0.25	0.41	0.37	0.034	0.021
20	0.26	0.25	0.41	0.023	0.040

TABLE 5. APPARENT DISTANCE BETWEEN FLASHING LIGHTS

Round	mean (m)	rms error (m)	standard deviation (m)
6	0.9494	0.0063	0.073
9	0.9273	0.0018	0.026
10	0.9251	0.0024	0.033
11	0.9240	0.0017	0.026
12	0.9128	0.0048	0.025
13	0.9310	0.0024	0.022
14	0.9589	0.0108	0.058
15	0.9429	0.0023	0.037
16	0.9327	0.0058	0.086
17	0.9252	0.0015	0.023
18	0.9268	0.0029	0.042
19	0.9188	0.0030	0.029
20	0.9214	0.0017	0.018

Tables 6 and 7 show information on the flash rate of each vehicle. Although the flash rate was measured in the laboratory, it became apparent early in the programme that the flash rate during the trial was not necessarily the same as that measured in the laboratory even though it generally remained steady throughout each flight. On those rounds carrying telemetry transmitters, the flash pulses were fed to the transmitter thus providing a monitoring facility and the results from these rounds are shown in Table 7. A method of measuring the flash rate was developed for the last five trials, using a movie camera with timing attached. The adjusted flash rates given in Table 6 for rounds DFL16 onwards are from that source. In those trials for which neither telemetry nor movie camera records were available we had to rely on estimates of the gravitational acceleration to provide information on flash rates. The nominal flash frequency, f', which was measured in the laboratory, was used initially to estimate timing for the trajectory data. The apparent gravitational acceleration was estimated by numerical differentiation of the trajectory data using this approximate timing. This apparent value, g', was used to adjust the flash frequency according to the relation

$$f = f'(g/g')^{1/2},$$

so that the data was consistent with the known value, $g=9.797\ ms^{-2}$. The resulting flash rates are given in Table 6 for all vehicles except DFL6 because trajectory data was too noisy to provide a reasonable estimate of (g/g') and because flash rate was monitored by telemetry. Where independent estimates of flash rate are available, agreement is fair, although the flash rates obtained solely from estimated acceleration due to gravity are not as reliable as those from other sources. However the accuracy of the flash rate is not a critical factor in the derivation of aerodynamic coefficients because of their non-dimensional nature. Consequently, we do not expect any significant errors in the results to arise from small errors in the flash rate.

TABLE 6. ESTIMATED FLASH RATES

Round	Nominal Flash Rate (Hz)	$(g'/g)^{1/2}$	Telemetry (Hz)	Movie Camera (Hz)	Adjusted Flash Rate (Hz)
6	30.76	-	30.76	-	-
9	30.41	1.054	-	-	28.86
10	25.41	0.992	-	-	-
11	32.58	1.003	-	-	-
12	31.60	1.06	-	-	-
13	27.10	0.908	-	-	29.86
14	31.75	1.14	-	-	-
15	35.45	1.012	34.90	-	35.02
16	30.8	1.055	-	29.90	29.9
17	32.3	1.044	-	31.03	31.03
18	29.60	0.976	-	29.48	29.48
19	30.14	0.995	29.90	29.89	29.89
20	30.90	1.018	29.89	29.89	29.89

NOTE: The acceleration due to gravity in the vicinity of the gas gun range is $g = 9.797\ m\ s^{-2}$.

TABLE 7. TELEMETRED FLASH RATE BEHAVIOUR

(a) Starting pulses for DFL6

Pulse	Time (s)	Duration (ms)	Time interval (s)
1	0.	6.1	0.
2	0.0388	0.5	0.0388
3	0.0570	32.4	0.0182
4	0.1216	0.4	0.0646
5	0.1543	0.4	0.0327

(b) Statistics of flash interval

Round	$\bar{\delta}$ (s)	$\sigma(\bar{\delta})$ (s)	$\sigma(\delta)$ (s)	f (Hz)
6	0.032503	0.000019	0.000128	30.76
15	0.028647	0.000051	0.000861	34.90
19	0.0334	0.001	-	29.9
20	0.033454	0.000007	0.000075	29.89

NOTE: $\sigma^2(\bar{\delta}) = \sigma^2(\delta)/N$, where N is the number of samples.

3.1.1 Round DFL6

The sabot used in launching this model proved to be unsatisfactory. The fact that rounds DFL7 and DFL8 did not survive launch, can be largely attributed to the sabot. Although DFL6 did survive the launch, the separation disturbance was quite large, generating an initial oscillation with incidences of about 60°. In addition, camera records were poor near the beginning of the trajectory. The high noise levels indicated by the results in Tables 4 and 5 are mainly a result of the poor quality of the early data. Estimates of the flash rate of the nose and tail lights are not presented in Table 6 because flash rate data was obtained via the telemetry link. As a consequence this was one of the few rounds where we were able to conclude positively that the flash rate in flight was the same as that measured in the laboratory. The only anomalous behaviour occurred in the timing and duration of the first three flashes, listed in Table 7(a). From the fourth flash onward the flash rate was maintained at its nominal frequency and the root mean square variation of the time interval between flashes was about 0.4% of the time interval.

3.1.2 Round DFL9

The data obtained from this round was generally of good quality although as one can see from Table 6 the flash rate in flight varied significantly from the laboratory measurements.

3.1.3 Round DFL10

The flash rate was close to the nominal value for this trial as one can see from Table 6, but it was slightly erratic for the first 1.25 seconds, varying randomly by as much as 3 percent. The data for this period was difficult to analyse. Tables 4 and 5 show that overall, however, the data was generally of good quality.

3.1.4 Round DFL11

The results for DFL11 were similar to those for DFL10 in that the flash rate was slightly erratic for the first 2 s, again varying randomly by as much as 3 percent. However, unlike DFL10 the data was generally of below average quality as far as the noise levels given in Table 4 are concerned.

3.1.5 Round DFL12

Two cameras malfunctioned during this trial and as a result only a very short section of the trajectory was covered by the cameras. The data available covers slightly less than one pitch cycle. Consequently this trial has been repeated.

3.1.6 Round DFL13

The emulsion on the camera plates used in this trial had deteriorated badly, possibly through overlong storage, and the plates were badly fogged. As a result no tail light position measurements were obtained before about 4 s and by that time the oscillations caused by the release disturbance had damped out. Therefore, no data was obtained on the angular motion of the bomb. However, it was possible to estimate the axial force coefficient accurately. It was also possible to estimate the flash rate quite accurately and Table 6 shows that this was almost 10 percent higher than the value expected. Because of the complete absence of data on tail position, this trial has also been repeated.

3.1.7 Round DFL14

Very little useful data was obtained from this trial. Both camera 2 and camera 3 failed to operate and the plates from the other cameras, 1 and 4, were so heavily fogged that very few of the images from the tail light could be distinguished. This trial too was repeated.

3.1.8 Round DFL15

This trial produced a very good set of data. Tables 4 and 5 show that the quality of the data was in all respects as good as that obtained from any other trial. A magnetometer record was obtained for the whole of the flight and this included the flashing light pulses. The data obtained from this record of the flash rate is presented in Table 6 and Table 7(b). It shows that the flash rate was slightly different from the nominal value. The measured value agrees with the value estimated from the apparent gravitational acceleration and listed in Table 6. The standard deviation of the flash interval listed in Table 7 is much larger than that of DFL6 and this indicates some erratic behaviour of the flash rate, but it is insufficient to cause any significant inaccuracies in the results derived from the data.

3.1.9 Round DFL16

This trial repeated DFL13 and was much more successful. However, despite the good quality of the camera records, the noise levels shown in Tables 4 and 5 were amongst the highest for the whole series. However, there was good coverage of the trajectory, particularly the initial pitch oscillations and this enabled us to derive reasonably good results from the trial. In addition, the roll light has provided some useful information on roll behaviour.

3.1.10 Round DFL17

This was the second trial in the series of three repeated ones. It provided backup results for DFL12. Quality of the results was generally good, with low noise levels according to the estimates given in Tables 4 and 5. Roll rate data was obtained from the roll light.

3.1.11 Round DFL18

This was the final in the series of three repeated trials and provided backup data for DFL14. Data quality was generally below average because of the poor quality of the ballistic camera records. Flashing light images were faint and many of the tail light images were missing altogether. In addition, problems in reconciling the calibration of the camera plates using the range reference light system could not be wholly resolved, and so there were inconsistencies between the different cameras. Consequently, there were high noise levels and some gaps in the data. No useful data was obtained from the roll light. Despite these problems, sufficient data was obtained to provide reasonably accurate estimates of the aerodynamics.

3.1.12 Round DFL19

This was the first of two rounds fired in a program for further development of the flashing light trials technique. However, the data obtained from the trial provides further information for this series of trials and is included here. The ballistic camera records were again of very poor quality but there were no problems with calibration of the plates and consistency between cameras was generally fair. No data was obtained from the roll light because of the poor quality of the camera plates. Data from the magnetometer was obtained only for the second half of the trial, owing to a frequency shift in the telemetry transmitter at launch. Consequently, rolling moment and flash rate information from DFL19 is not as accurate as for the other rounds for which telemetry records are available.

3.1.13 Round DFL20

This, the second vehicle for further development of the flashing light trials technique, was successful; noise levels are generally low and good data was obtained from both flashing lights, from the roll light and from the magnetometer. Both roll data and flash rate data from the magnetometer telemetry were of good quality.

3.2 Data analysis results

There are essentially two separate aspects of the data analysis. On the one hand we have the flashing light data, from which estimates of axial force coefficient, C_x, derivative of the normal force coefficient, $C_{z\alpha}$, derivative of the static pitching moment coefficient, $C_{m\alpha}$, and the derivative of the pitch damping moment coefficient, $C_{mq}+C_{m\dot{\alpha}}$, have been derived. In addition to these basic linear aerodynamic derivatives it has been possible to estimate some nonlinear terms, when data from trials has been of particularly high quality and when the amplitude of incidence oscillations has been sufficiently large. The simple nonlinear model, which has been used, assumes that the normal force and pitching moment coefficients can be represented in the form,

$$C_z = C_{z\alpha}\alpha + C_{z\alpha 3}\alpha^3;$$

$$C_m = C_{m\alpha}\alpha + C_{m\alpha 3}\alpha^3.$$

Attempts to estimate Magnus moment derivatives have shown that the effect of the Magnus moment on the pitching motion of the bomb, at or below the equilibrium roll rate of 5 Hz, is not significant.

The second set of results which is much less comprehensive than the first set, consists of values for the rolling moment coefficients, C_l, and roll damping derivatives, C_{lp}. The estimates for these coefficients were obtained principally from the magnetometer data, with some backup from the roll light data.

The results derived from the flashing light data are discussed in the first part of this subsection while the results of analysing the roll rate data are described in the second part.

3.2.1 Flashing light results

The values of aerodynamic coefficients derived from the flashing light data are summarised in Tables 8 and 9 and figures 5 to 9. Let us look first at the axial force or zero incidence drag results given in figure 5 and Table 8. The most obvious characteristic of the axial force results is the startling difference between streamlined vehicles and vehicles with lugs and fuses. The mean value of the axial force coefficient for a streamlined bomb is -0.123 and for one carrying lugs and fuses is -0.241, so that the addition of two lugs and nose and tail fuses increases the axial force on the bomb by 100%. After allowing for the lower skin friction at the flight Reynolds number and the base pressure effects , the wind tunnel measurements(ref.4) are seen to be consistent with the free flight results. The results for the bomb with lugs and fuses also agree well with the flight results of reference 5, allowing for the drag of the T lugs used here, instead of the eye lugs used in the flight trials described in reference 5.

Consider now the results in figures 6 and 7 for the normal force derivative and the pitching moment derivative. Since the amplitude of the incidence oscillations used to determine the derivatives is generally large, maximum incidence values are given in Table 8. The wind tunnel values of $C_{m\alpha}$ and $C_{z\alpha}$ quoted for comparison purposes represent average slopes over the range from 0° to 10° incidence. We estimate that 90% of data points lie in this range. Figures 6 and 7 show that there is general consistency amongst $C_{z\alpha}$ and $C_{m\alpha}$ estimates from most trials and the results are generally in good agreement with wind tunnel results. It should be remembered that these estimates are average values over a variety of incidence ranges so that some of the scatter of free flight results can be attributed to this variation as well as the small discrepancies between free flight and wind tunnel results. There is clearly a significant contribution to both these discrepancies from measurement error. Overall, the wind tunnel results for pitching moment provide a good representation of the flight data averaged over all trials, even when the bomb has lugs and fuses. There is a significant improvement in the stability of the bomb when the tail is modified even at the low Mach numbers of these tests. The results are not sufficiently good to enable us to quantify the improvement accurately, but the centre of pressure appears to have shifted rearward by about 0.1 calibres.

TABLE 8. DERIVED LINEAR AERODYNAMICS

Round	C_x	$C_{z\alpha}$	$C_{m\alpha}$	$C_{mq}+C_{m\dot{\alpha}}$	α_{max}	ε	n
6	-0.121 (0.013)	-3.2 (0.40)	-3.11 (0.054)	-98 (9)	37°	0.058	80
9	-0.254 (0.004)	-4.0 (0.20)	-3.06 (0.008)	24 (2)	7.5°	0.019	163
10	-0.113 (0.002)	-4.0 (0.32)	-4.1 (0.064)	-160 (10)	16°	0.026	80
11	-0.130 (0.002)	-4.9 (0.48)	-4.9 (0.07)	-136 (12)	16°	0.028	95
13	-0.127 (0.001)	-	-	-	-	-	160
15	-0.230 (0.001)	-4.9 (0.30)	-4.23 (0.033)	-138 (5)	22°	0.017	88
16	-0.125 (0.002)	-4.6 (0.29)	-4.76 (0.051)	-152 (9)	14°	0.018	89
17	-0.235 (0.006)	-5.6 (0.39)	-5.39 (0.069)	-152 (12)	27°	0.042	79
18	-0.230 (0.002)	-4.9 (0.54)	-4.69 (0.088)	-161 (15)	20°	0.040	153
19	-0.256 (0.006)	-4.9 (0.31)	-4.84 (0.064)	-153 (12)	16°	0.025	69
20	-0.123 (0.003)	-4.8 (0.28)	-5.21 (0.050)	-151 (9)	21°	0.030	110
WT	-0.124	-4.2	-5.2	-130			

NOTE: (1) Wind tunnel measurements quoted are average values, for a streamlined bomb with a standard tail, over a range of incidence from 0° to 10°. Wind tunnel measurement of axial force is corrected both for the lower skin friction at the flight Reynolds number and for base pressure.

(2) Numbers in brackets beneath each result are estimated rms errors in each.

(3) ε is an overall error indicator, representing the root mean square value of the weighted residuals of the experimental measurements relative to the simulated values.

(4) n is the number of trajectory data points used.

While the majority of results are consistent DFL6 and DFL9 show larger departures from the mean than might be expected. In both cases these differences can be attributed to the unusual flight behaviour of the round. The first, DFL6, suffered an almost catastrophic release disturbance with initial incidences approaching 70°. In addition, the rms error of the fit given in Table 8 shows that this trial has the worst correspondence between the theoretical model of the motion and the experimental measurements. This poor matching occurred in spite of the fact that some initial data was discarded so that maximum incidence for the section of the data analysed was 37°. Round DFL9 showed similar behaviour to that observed on some of the trials described in reference 5. The vehicle exhibited slightly undamped coning motion. It precessed about zero incidence with an initial amplitude of about 5°, growing to 7.5° over a five second period, and with a frequency of slightly less than one hertz. The roll rate during this period was between four and five hertz. The linear aerodynamic model cannot properly describe such motion and so the results for DFL9 are not accurate.

TABLE 9. NONLINEAR AERODYNAMICS

Round	$C_{z\alpha}$	$C_{z\alpha 3}$	$C_{m\alpha}$	$C_{m\alpha 3}$	$C_{mq}+C_{m\dot{\alpha}}$	ε
6	-3.2	-9.	-3.02	-3.2	-97	0.058
	(0.62)	(5.1)	(0.12)	(1.5)	(7)	
10	-4.0	-6.	-2.32	-58.	-107	0.022
	(0.46)	(10.0)	(0.12)	(5.5)	(7)	
11	-4.5	-11.	-3.64	-51.	-97	0.025
	(0.76)	(21.7)	(0.15)	(6.1)	(11)	
15	-4.9	0.	-4.21	-1.	-138	0.017
	(0.52)	(6.3)	(0.07)	(1.7)	(6)	
16	-4.0	-22.	-3.67	-74.	-138	0.017
	(0.46)	(17.0)	(0.09)	(6.2)	(7)	
17	-4.5	-8.	-4.45	-15.	-144	0.040
	(0.61)	(5.9)	(0.13)	(2.2)	(12)	
18	-4.7	-41.	-3.57	-51.	-122	0.039
	(0.68)	(22.0)	(0.16)	(11.1)	(12)	
19	-3.5	-40.	-3.88	-37.	-136	0.022
	(0.49)	(12.0)	(0.11)	(5.2)	(9)	
20	-4.3	-14.6	-4.19	-26.2	-128	0.028
	(0.48)	(8.0)	(0.09)	(2.9)	(7)	
WT	-3.8	-12.	-3.08	-40.2	-130	

The results for pitch damping coefficient shown in figure 8 and Table 8, are quite consistent, excepting once again those results for DFL6 and DFL9 which differ significantly from the remainder for reasons which we have already discussed. The average value of -152 is slightly higher than the wind tunnel measurement but the discrepancy is within the limits allowed by measurement errors in both free flight and wind tunnel results.

The above results were all obtained using a linear model for the aerodynamics. Because of the large incidence amplitudes which all the vehicles experienced and which are characterised by the maximum values in Table 8, a nonlinear model with a cubic representation of normal force and pitching moment was also fitted to the data. The mathematical expressions used for each are given at the beginning of this section. The results of the analysis are given in Table 9 and figure 9 covering those rounds for which estimates of nonlinear effects could be made. The improvement in the mean square difference between the model and the data ranges from insignificant for DFL6 and DFL15, up to almost 20% for DFL10. The estimates of pitch damping coefficient have decreased slightly and the average value is -126. The variations of normal force and pitching moment are shown in figure 9. Comparison of linear and cubic coefficients quoted in Table 9 can result in overestimates of the scatter of results because of the correlation between the two terms. This correlation leads to compensation of overestimation of one by an underestimation of the second, so that the curves in figure 9 provide a better basis for comparison of the various results. As in the case of the linear model, results for DFL6 differ markedly from the remainder. In addition, the estimated pitching moment coefficient from DFL10 also differs significantly from the majority of the results. Apart from these results there is not a great deal of scatter amongst the results from the various flight trials. The results tend to diverge as incidence increases, because there are very few data points at higher incidences. Vehicle DFL16 for instance has only 5 points at incidences greater than 10°, and as is apparent from Table 8 most of the trials provided very little or no data for incidences greater than 15°. The wind tunnel results for C_z and C_m are given in figure 9 for comparison purposes. The results shown are for a roll orientation of 22.5°, which corresponds to the average values of the coefficients over one roll cycle of the bomb.

3.2.2 Rolling moment results

Two sources of data were available to provide information on the rolling moments. Roll magnetometer data was obtained from DFL6, DFL15 and DFL20. Roll rate measured from a continuous light source carried in the vehicle was obtained for DFL16, DFL17 and DFL20. The magnetometer data was analysed using a simple parameter estimation method and the results are given in Table 10. The result for 20(b) refers to the analysis of the magnetometer record for DFL20 while that for 20(a) refers to the analysis of the roll light data. The data from the roll lights was not as detailed or as accurate as the magnetometer data but was analysed using a similar parameter estimation method. The results are also listed in Table 10 but are much less accurate. In general only 20 to 30 data points were available. Unfortunately, it was not possible to correlate the timing between the flashing light records and the magnetometer telemetry data accurately enough to include in the analysis any effects of incidence on rolling moment, except in the case of DFL20. DFL20 was fired specifically to provide data for testing of data analysis methods designed to extract information on the cross coupling effects of roll and incidence behaviour. The results from such testing will be reported separately.

The rolling moments are modelled such that roll acceleration is represented in the form

$$\dot{p} = (QSd/I_x)\ \{C_l + C_{lp}(pd/2V)\},$$

where C_l represents the rolling moment due to fin cant and C_{lp} represents the roll damping moment. Both parameter estimation methods of data analysis operate similarly in determining values for C_l and C_{lp}.

The rolling moment coefficient, C_l, is determined from the data at the beginning of the trajectory where the roll acceleration is high and the roll rate is low. The ratio of rolling moment coefficient to roll damping derivative is determined from the data obtained later in the trajectory when the roll rate is near equilibrium so that the roll acceleration is small and the roll rate is relatively large. The problem with the rolling moment results, particularly with DFL6, is that large incidence oscillations during the early part of the trajectory cause large changes in the rolling moment so that the estimate of C_l is badly degraded. As a consequence the estimate of C_{lp} will also be in error. The ratio C_l/C_{lp} quoted in the last column of Table 10 is generaly more consistent because this is determined from the data measured later in the trajectory when incidence oscillations have become damped. This ratio is consistently lower for free flight than for wind tunnel, which suggests that in free flight the fins provide more effective roll damping.

TABLE 10. ROLLING MOMENT COEFFICIENTS

Round	C_l	C_{lp}	C_l/C_{lp}
6	0.0739	-3.17	-0.0233
15	0.0214	-0.713	-0.0300
16	0.0223	-0.906	-0.024
17	0.0223	-0.957	-0.024
20(a)	0.0267	-1.302	-0.022
(b)	0.0216	-0.933	-0.0231
WT 0°	0.0200	-0.75	-0.0267
10°	0.0256	-0.95	-0.0269

4. SUMMARY OF RESULTS

The results from low speed firings of 15 models of Mk82 bombs have been presented. Data was obtained from 13 of the trials, but only limited data from 3 of them. Thus 10 of the vehicles have provided good data and from 9 of them we have obtained useful estimates of nonlinear effects. Initially the object of the trials was to compare performance of the streamlined bomb and the performance of the bomb with lugs and fuses added. A second aim has been to compare these two configurations with similar configurations having a slightly modified tail cone and a third aim has been to use the complete set of results to assess generally the overall accuracy, reliability and repeatability of results obtained from the flashing light trials technique.

The most impressive aspect of the results is the 100% increase in drag at subsonic speeds due to the addition of lugs and fuses to the streamlined bomb. The magnitude of the increase first became apparent during the analysis of flight trials results described in reference 5. The increase in this case is even larger due to the use of T lugs suitable for the bomb racks of the F111 aircraft rather than simple suspension lugs used on the Alkan PM3 bomb beam.

The other important result of the trials was the flight behaviour of DFL9. Again, this behaviour is similar to that observed on some bombs during analysis of the flight trials described in reference 5. After the effects of the initial disturbance had become damped the bomb began to process with an initial amplitude of about 5°, which grew steadily at a rate of about 0.5° per second. It seems likely that the asymmetric flow caused by the lugs and tail fuse is providing the initial impetus to unstable dynamic flight behaviour which will result in quite large dispersions over long flight times.

Apart from these two observations the results from the trials were consistent with wind tunnel results. The scatter of results from individual trials was generally within the limits indicated by the estimated rms errors in each value. Except for the increased axial force due to lugs and fuses, differences between configurations with or without lugs and fuses were not sufficiently large to enable us to draw any positive conclusion about their significance. On the other hand, the modification to the tail cone resulted in a significant improvement in the static stability of the bomb. In general results obtained using a nonlinear representation of normal force and pitching moment resulted in a small but significant improvement both with regard to matching of model and data and with regard to reducing the differences between the flight results and the wind tunnel measurements.

Rolling moment estimates were obtained from several rounds but the scatter of results and the problems of cross coupling with incidence rendered these results less useful than expected. However, there was a general trend towards higher roll damping than that measured in the wind tunnel.

Finally, it has become apparent over the series of trials that when equal quantites of data are available, the better quality data will yield more accurate results. However, on occasions when we have good quality data the length of the experimental record is a significant factor in determining accuracy of results. Comparison of the variations in accuracy of the results obtained from the various trials provides a good illustration of this conclusion. Due to relatively large damping of the Mk82 bomb, generally only between three and four complete periods, where the pitch oscillations were of significant amplitude, were obtained from each trial. In cases such as DFL12 and DFL14 when data was missing for a significant portion of this early part of the trajectory the results for lateral aerodynamic derivatives were generally not meaningful. Even longer lengths of trajectory were required for accurate determination of the axial force coefficient, typically 3 to 4 s. A typical example of the quantity and quality comparison for axial force is given by DFL18 and DFL20. Table 5 shows that the standard deviation of the estimated distance between the nose and tail flashing lights for each point in the trajectory of DFL18 is approximately double that for DFL20. The results in Table 4 generally support the conclusion that the data for DFL18 showed a much higher noise level than that for DFL20. However, only 3.5 s of data was available for DFL20, whereas 7.25 s was available for DFL18. This is ample in both cases to determine the aerodynamic parameters accurately and to cover that part of the trajectory where the pitch oscillations show significant amplitude, but as Table 8 shows the estimated rms error in the value of C_x from DFL18 is still less than for most other trials, in particular less than for DFL20. On the other hand estimated rms errors in lateral aerodynamic coefficients are generally larger for DFL18, approximately in proportion to the noise levels in the trajectory data.

5. CONCLUSIONS

The following important conclusions can be drawn from the results of the firings of 15 models of the Mk82 bomb.

(1) The addition of nose and tail fuses and T-lugs to the Mk82 bomb doubles the axial force or zero incidence drag at subsonic speeds.

(2) Asymmetric flow effects resulting from lugs and fuses may cause unstable flight dynamic behaviour of the sort exhibited by DFL9.

(3) Overall, the free flight results agree well with each other and are consistent with wind tunnel measurements.

(4) There is a significant improvement in static stability due to the modified tail cone. The centre of pressure shift is about 0.1 calibres rearward.

(5) The roll damping measured in flight is slightly greater than that measured in wind tunnel tests.

(6) Records must be of adequate length if aerodynamic coefficients are to be determined accurately. The precision of the axial force coefficient is particularly sensitive to record length.

NOTATION

C_1	rolling moment coefficient
C_{1p}	roll damping coefficient derivative
$C_{m\alpha}$	pitching moment coefficient derivative
$C_{m\alpha 3}$	coefficient of cubic term in nonlinear pitching moment representation
$C_{mq}+C_{m\dot{\alpha}}$	pitch damping coefficient derivative
C_x	axial force coefficient
$C_{z\alpha}$	normal force coefficient derivative
$C_{z\alpha 3}$	coefficient of cubic term in nonlinear normal force representation
d	body diameter
f	flashing light frequency
g	gravitational acceleration
I_x	roll inertia
n	number of trajectory data points. For each data point we have measurements of x, y, z, Ψ and ϑ
p	roll rate
Q	dynamic pressure
S	reference area
V	true air velocity
$\begin{bmatrix} x \\ y \\ z \end{bmatrix}$	range coordinates, OX downrange, OY to the right and OZ vertically downwards
α	incidence
δ	time interval between flashes
$\bar{\delta}$	mean value of δ for the complete trajectory
ε	mean square error of model outputs
ϑ	elevation
σ	standard deviation
ψ	azimuth

superscripts

.	differentiation with respect to time

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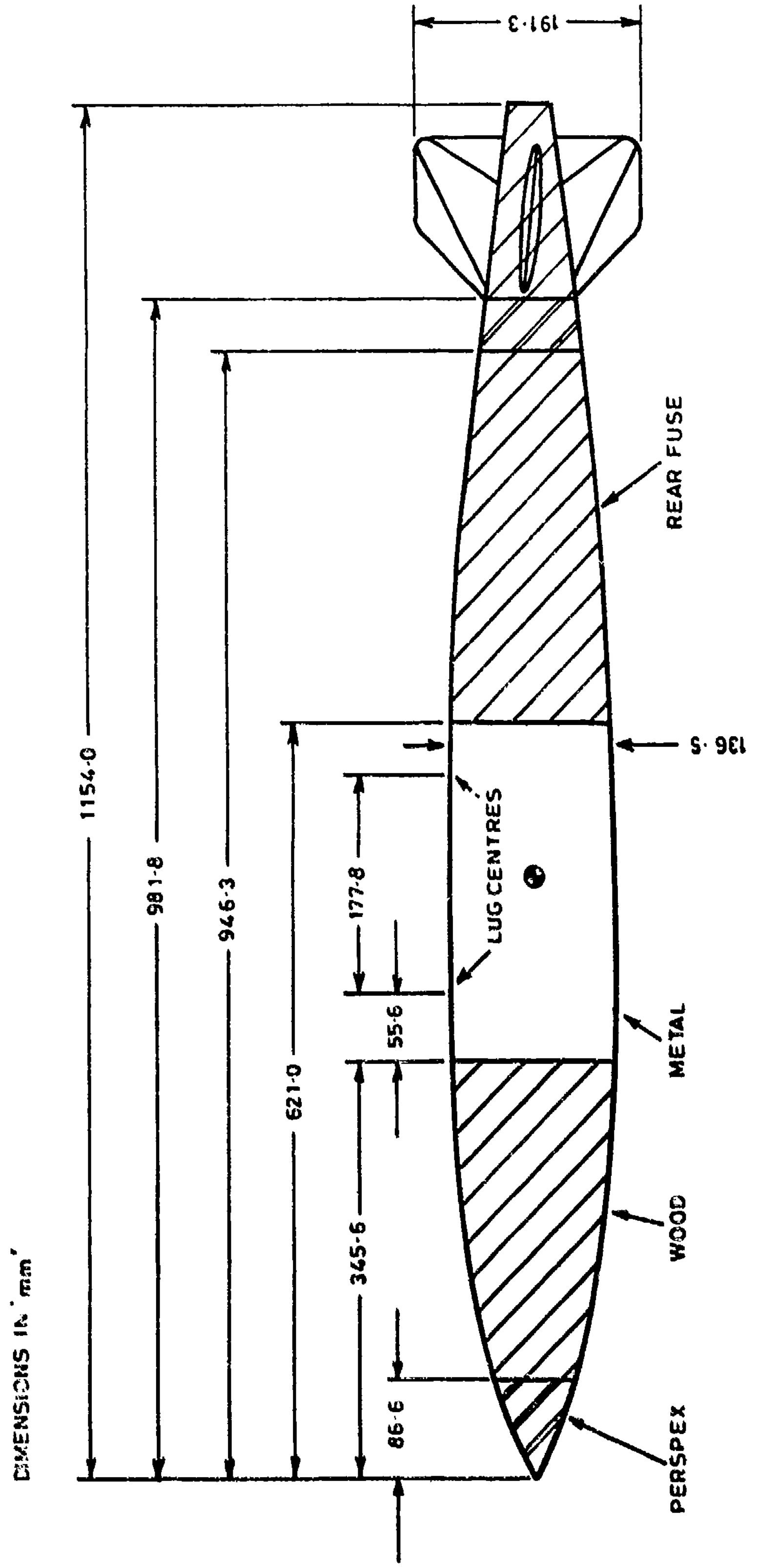
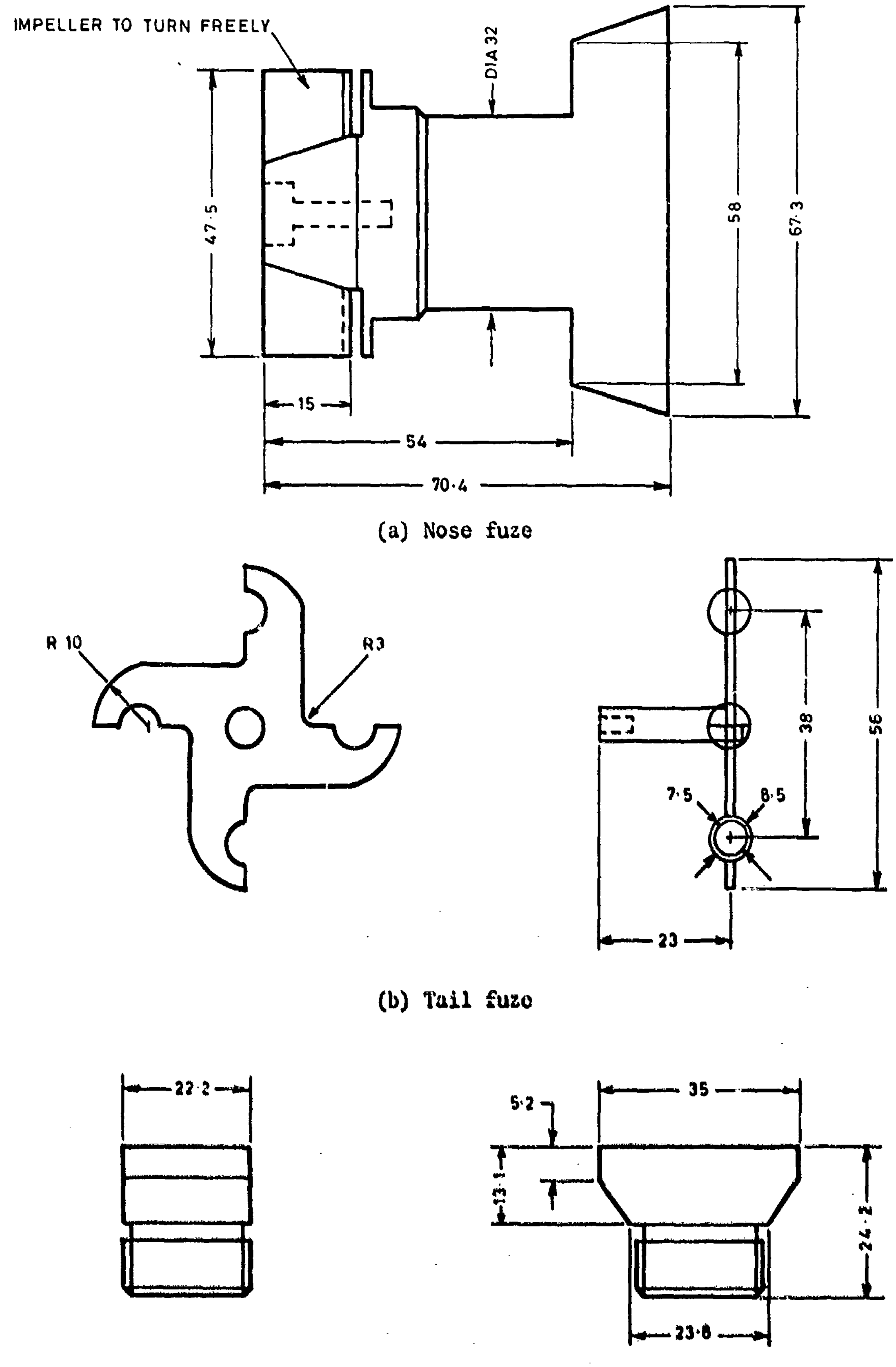


Figure 1. Streamlined model with unmodified tail



(a) Nose fuze

(b) Tail fuze

(c) Lugs

Figure 2. Lugs and fuses

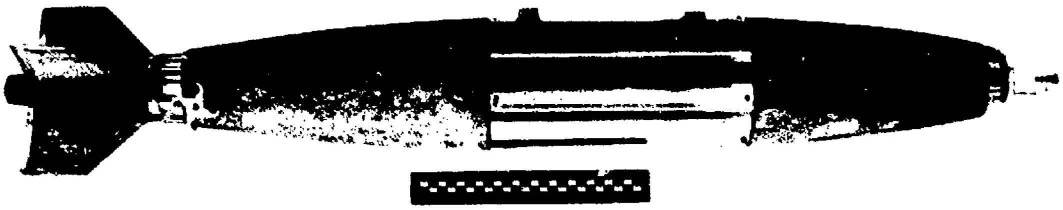


Figure 3. Model with lugs and fuses

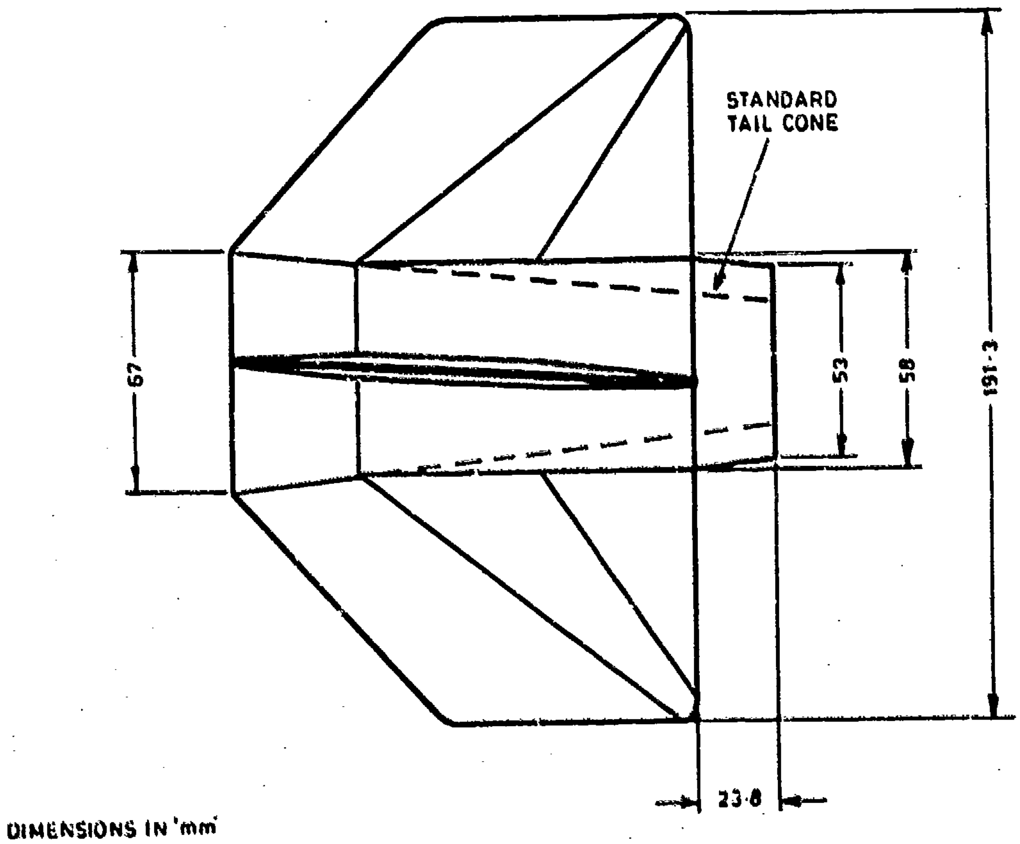


Figure 4. Modified tail

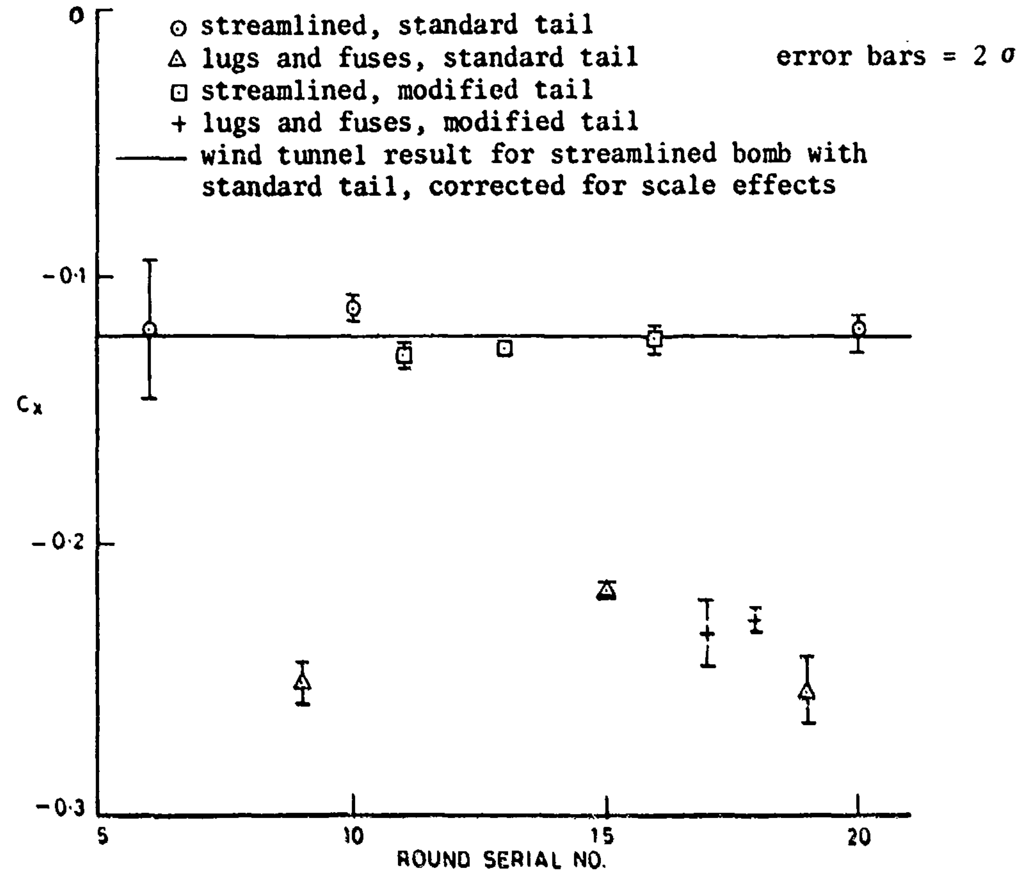


Figure 5. Axial force coefficient

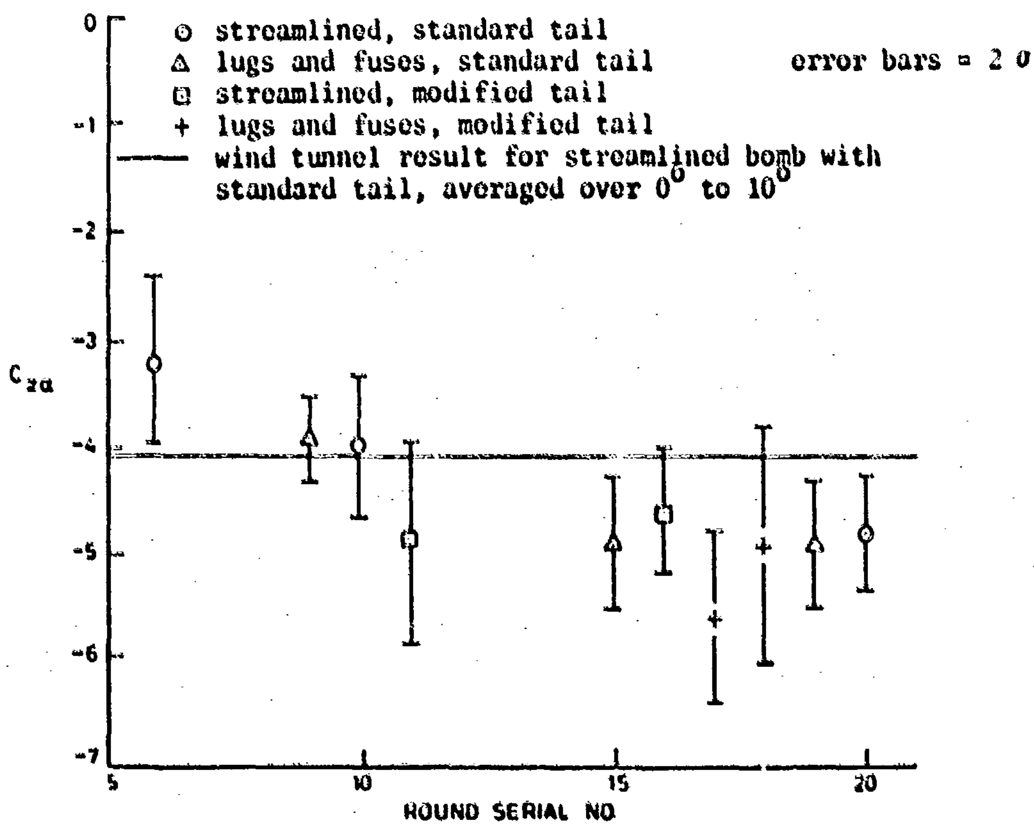


Figure 6. Normal force derivative

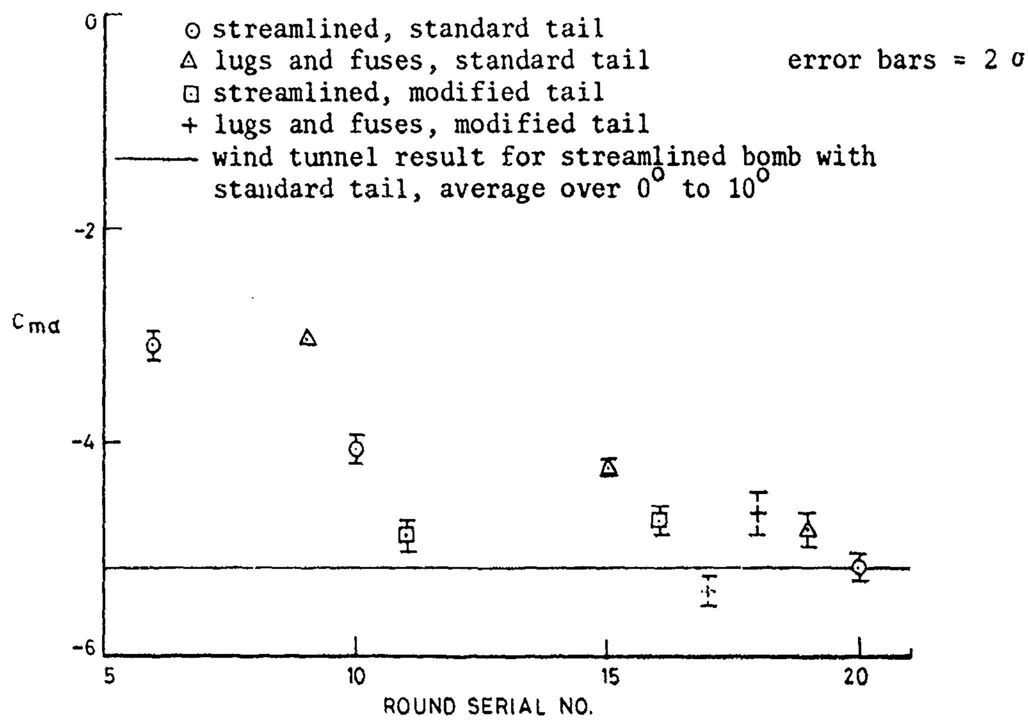


Figure 7. Pitching moment derivative

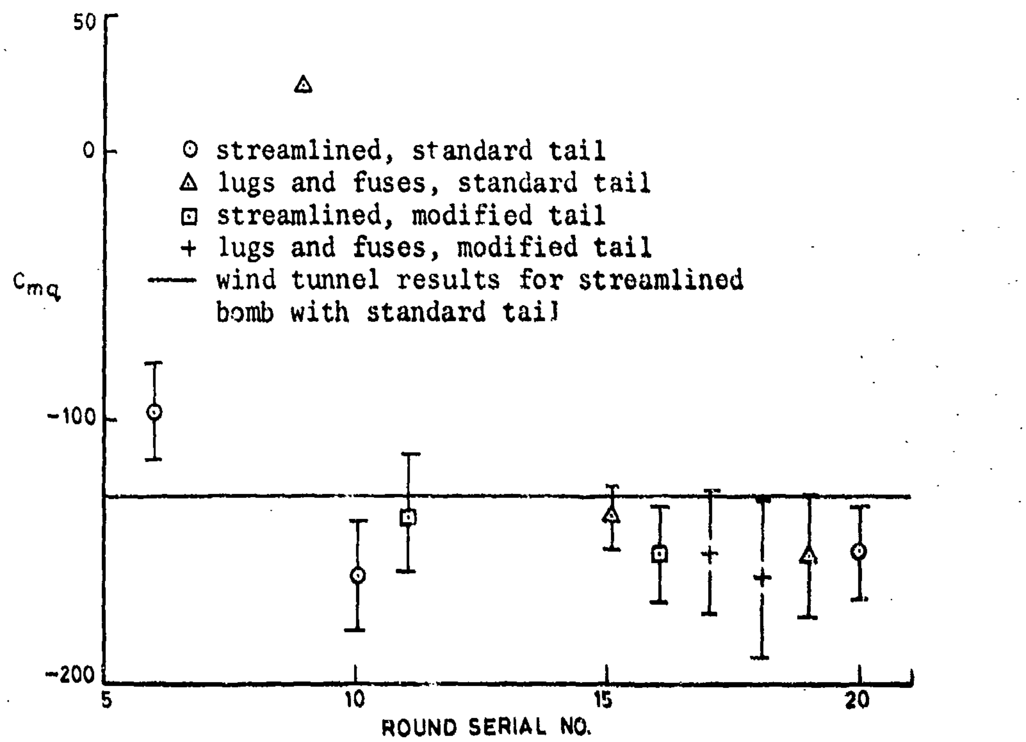
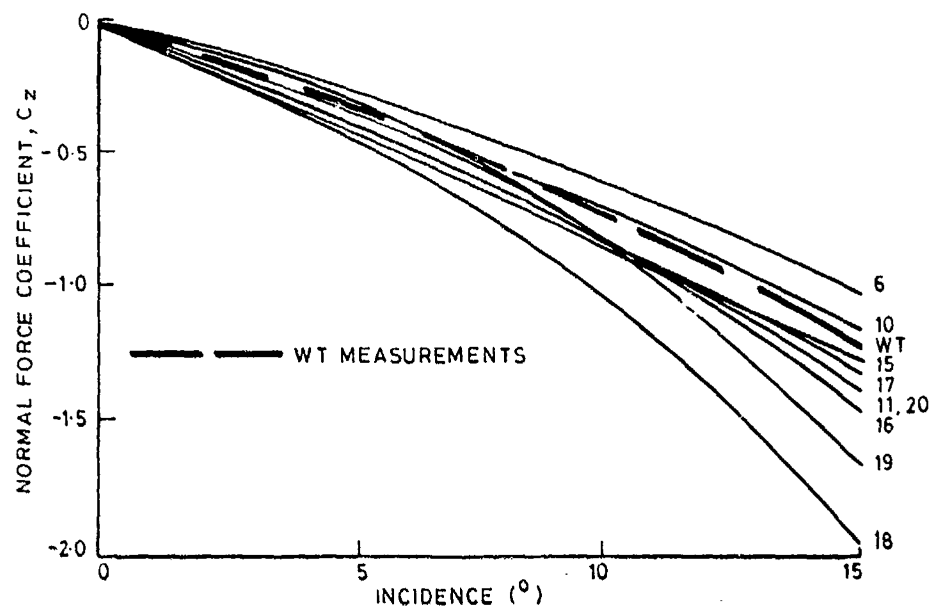
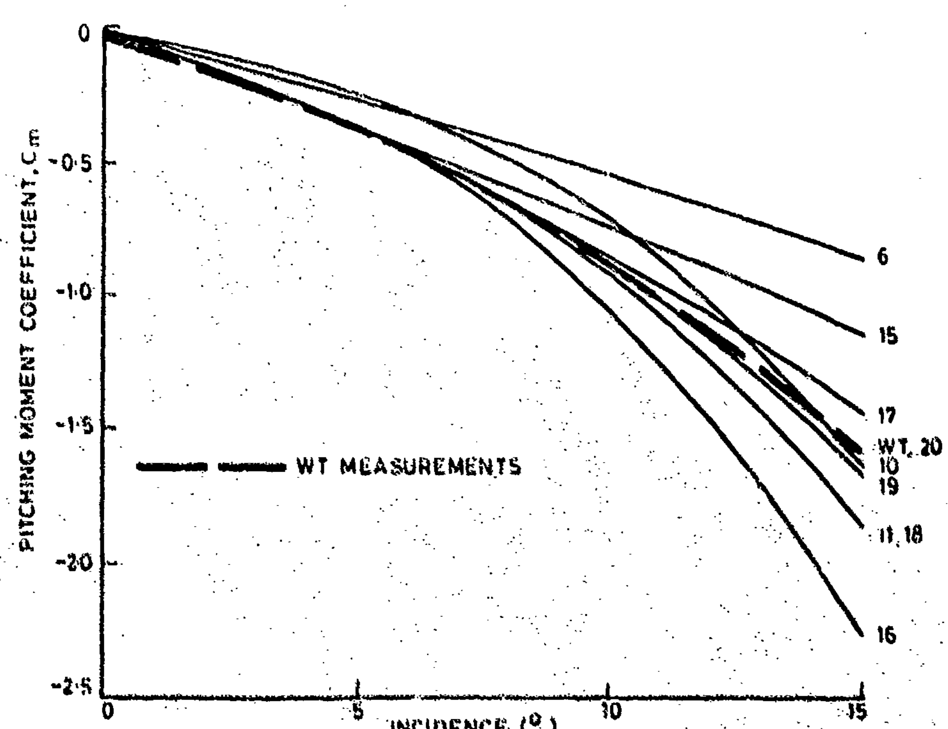


Figure 8. Pitch damping derivative



(a) Normal force



(b) Pitching moment

Figure 9. Nonlinear model results

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16 SUMMARY OR ABSTRACT:
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A series of fifteen 1/2 scale models of the Mk82 bomb has been fired from the Weapons Systems Research Laboratory gas gun with a nominal muzzle velocity of 120 m/s. The object of the trials was to compare the performance of various configurations, including streamlined models, models with lugs and fuses and some models with a modified tail cone. Three of the vehicles tested were the standard streamlined wind tunnel shape and the results from these are used as a benchmark in assessing the performance of the other configurations. Some of the trials were only partially successful and no data at all was obtained from two of the trials. However, all available results are presented and an assessment made of the relative performance of each configuration. Some comparisons are also made with wind tunnel measurements. The most striking aspect of the results is the 100% increase in drag resulting from the addition of lugs and fuses.

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